

CALIFORNIA  
ENERGY  
COMMISSION

# ADVANCED C8.3 NATURAL GAS ENGINE DEVELOPMENT PROGRAM

## FINAL REPORT

April 2002  
600-02-016F



Gray Davis, Governor

# CALIFORNIA ENERGY COMMISSION

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# **Advanced C8.3 Natural Gas Engine Development Program**

## **Final Report**

CONTRACT NO.  
500-98-018

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## **Acknowledgements**

Gas Research Institute and Cummins Engine Company wishes to thank the following individuals for their valuable contributions to this project:

Jerry Wiens, California Energy Commission  
McKinley Addy, California Energy Commission  
Mike Bogdanoff, South Coast Air Quality Management District  
Mike Frailey, NREL  
Mike Eaves, SoCal Gas  
Mike Bolin, SoCal Gas  
Richard Cromwell, Sunline Transit  
Rob Sessler, Viking Freight  
Chuck Crawford, Viking Freight  
Dan Wood, Viking Freight

## **Table of Contents**

Objective.....	4
Executive Summary .....	4
Project Details.....	5
Development Schedule .....	6
1. Design .....	7
1.1 ECM Hardware.....	8
1.2 Software .....	10
1.3 Harness design.....	12
1.4 Fuel Specifications .....	12
2. Performance Development .....	13
3. Engine Builds .....	15
4. Mechanical Development.....	15
5. Vehicle Demonstration.....	16
5.1 CTC Vehicle Tests .....	16
5.2 Field Test Engines.....	17
6. CARB / EPA Certification.....	20
7. Conclusions and Recommendations .....	23

## **PROJECT OBJECTIVE**

The objective of this project is to design, develop and implement a next generation electronic control system for the heavy-duty, natural gas C8.3G engine predominantly used in urban bus and truck markets. This control technology will enhance design robustness with regards to engine performance, emissions and sociability while maintaining ultra-low emission certification. The engine design and controls development will also allow a capability to use a wide range of natural gas fuel composition.

## **EXECUTIVE SUMMARY**

Cummins has been engaged in the development of lean burn natural gas engines for over a decade. A number of engine platforms have been developed and over time, the technology of these engines has evolved from mechanical subsystems to electronic engine management control. Natural gas engine electronic control management (ECM) systems were developed in early 1990s and have become a limiting factor in engine performance and emission enhancements. As natural gas engines become more mainstream products, their technologies have to keep pace with the larger volume, heavy-duty diesel platforms.

This project, described as the C8.3G Plus, was planned to develop and implement a modern electronic engine management system with the C8.3G engine. These are based on diesel engine core based control systems. The engine was also redesigned for performance enhancement and capability to use wide range fuel composition.

The project elements included: CM556 (Control Module 556; the name of the ECM platform) development, design for engine-mounted electronic controller and sensors, engine performance and mechanical development, vehicle field tests, emission certification, and product launch. The design of the electronic controller hardware and software was completed, verified, and released for production. The CM556 has provided a significant comparative advantage over the existing CM420 with respect to increased memory, speed, input/output, and application specific features. The implementation of CM556 has facilitated full control of air/fuel handling and drive-by-wire function, and eliminated a separate governor control module. The design, performance, and reliability of the engine and the new control system were validated through extensive engine dynamometer, bench tests, and a field test program consisting of ten vehicles in truck and bus service. The capability to operate on a wide range of natural gas compositions as low as 65 Methane number was also verified in the laboratory.

The C8.3G Plus engine has been tested for emission certification protocol including Supplemental Emission Tests (SET). The certification engine test results are; 1.53 g/bhp-hr NO<sub>x</sub> and 0.008g/bhp-hr PM. These are significantly better than the base C8.3G engine certification data. This recipe includes an oxidation catalyst in the exhaust system. The California Air Resources Board (CARB) has certified the engine to the optional low NO<sub>x</sub> standard of 2.0 g/bhp-hr. The US EPA has certified the engine to be within ULEV emission standards. A family emission level for NO<sub>x</sub> was established at 1.8 g/bhp-hr. The Supplemental Emission Test (SET) required for post 10/02 certification test results showed good compliance. This data will be used to certify the engine to that standard at a later date.

A parallel program developed and delivered the electronic Service Tools and publications required, complimenting the product launch for the field support organization. A service tool (Insite) and publications were developed and released to the field organization. The C8.3G Plus engine was launched into production in July 2001. A number of engines have been produced and are now in revenue service. The customer acceptance has been very positive. The project has met all its deliverables.

## **PROJECT DETAILS**

### **Development Schedule:**

The overall schedule of development is shown below in a milestone chart. The development plan was initially divided into two projects:

- The C+ project developed the control system and the overall engine design
- The C++ project developed the WRFC (Wide Range Fuel Capability) and knock control

Two separate launch dates were planned for these two projects with the C+ leading by 6 months. These two projects were later combined into one engine launch with combined deliverables.

All the development tasks shown in the schedules are shaded signifying that they have been completed. The program has met the objectives of the development of next generation electronic control module and sensors and lower emissions. The project surpassed the deliverables in emissions and the WRFC areas.

The project achieved lower engine emissions than targeted. The plan included an engine power de-rate in conjunction with the WRFC. The project was able to achieve the WRFC rating without an engine power de-rate. Overall, the project was behind schedule but completed all the tasks except humidity sensor implementation. This was not a deliverable for this program but an added feature that was expected to improve engine variability in service. Issues with this sensor prevented its inclusion for the product launch. Resource availability and technical issues were encountered which resulted in the delays outlined in the schedule. Issues were overcome, however, and the product was launched with success.

## C+ DEVELOPMENT

			'9 9												'0 0												'01											
#	MILESTONE	RESP	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J									
1	Concept Design Completed	JRD	A																																			
2	Concept Demo @CTC	MMK		A																																		
3	Harness Concept Design	JVD			P	A																																
4	Controller Calibration Completed	JVD				A																																
5	Prototype Engine for CDC	MMK			P	A																																
6	CTC Vehicle Tests	JVD			P								A																									
7	Knock Sensor Location Determined	DLD				P			A																													
8	Module and brackets Vibration Tests	JAM				P			A																													
9	CVS Emissions Measurements	DLD				P								A																								
9.1	Resolution of Turbo Stability Issue	DLD											A																									
10	Field Test Calibration & Software Com	SA					P					A																										
11	FMEA Completed	JRD					P	A																														
12	Design Freeze	JRD					P	A																														
13	Field Test Engines Available (4+6kits)	MMK						P				A																										
13.1	Field Test Engines/Kits Shipped	JRD											A																									
14	"D" Release Completed	MCS							P										A																			
15	Software Diagnostics Completed	SA										P						A																				
16	FMEA Issues Closure	JAM											P		A																							
16.1	Pistone design Defined	DLD												A																								
17	System Prototype Build with ESDN	DLD											P								A																	
18	Software Release with Knock Control	SA												P							A																	
19	Preproduction Build (3 Engines)	JH													P							A																
20	Field Test Issues Resolution	SA														P											A											
21	Endurance Tests Completed	JAM														P										A												
21.1	Field Test Power Cylinder Update	JAM															P					A																
22	Controller "P" Qualification Completed	SA															P					A																
23	"L" Release Completed	MCS																P					A															
24	Final Performance & Software Comple	DLD																P							A													
25	"PPAP" Completed	JRD																	P									A										
26	Certification	DLD																		P							A											
27	Limited Production	MMK																										P	A									

## C++ DEVELOPMENT

'0 0															'0 1					
#	MILESTONE	RESP	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J
1	Composition Analysis	DLD		P	A															
2	Piston Design	JAM		P		A														
3	System Concept Design	DLD			P		A													
4	Knock Control Demonstration	SA				P									A					
5	Performance Calibration for 275HP/750FT.Lb	DLD					P		A											
6	Fuel Composition Sensitivity Testing	DLD						P	A											
7	Redesign / Design Freeze	MMK							A											
8	"D" Release Completed	MCS								A										
9	Performance Calibration for WRF Configuratio	DLD									A									
10	System Verification	DLD										P					A			
11	Field Test Start	MMK										P		A						
12	Fuel Composition Standard Released	DLD											P						A	
12.1	Humidity Sensor System Released	SA													P				S	
13	Endurance Testing Completed	JAM														P	A			
14	"L" Release Completed	JAM																P	A	
15	Final Performance Recipes (WRF&Humidity)	DLD																P	A	
16	"PPAP" Completed	JAM																P		P
17	Certification	DLD															A		P	
18	Limited Production	MMK																		P

P = Plan , A = Actual , F = Forecast , S = Suspended



## 1. Design

All design process requirement and product definition work were completed and the product was released to the producing plant (CDC). Some supply and option issues remained after launch but those have been resolved following normal issue correction processes. The new design allowed the following features for the engine:

- Eliminate Woodward governor
- Wide range fuel composition capability
- Knock sensing and control
- Robust Oxygen sensor design
- Improved oil consumption
- Improved throttle actuator
- Adaptive learn
- Modern engine controller
- Improved controls
- More sensed parameters



## 1.1 ECM Hardware

Considerable controller capability enhancements have been attained with the new ECM. The table below outlines a comparison between the CM420, which was the production controller for all Cummins gas engines, and the new CM556 controllers. The CM556 is a derivative of the CM550 engine controller recently launched on the IS family of midrange diesel engines at Cummins.

<u><b>CM556</b></u>	<u><b>CM420+Governor</b></u>
<ul style="list-style-type: none"><li>• 512k (bytes) Flash</li><li>• 64K RAM</li><li>• 8K EEPROM</li><li>• Wide range Oxygen Sensor</li><li>• Integrated engine and Speed Controls</li><li>• J1708/1587 and J1939 datalinks</li><li>• Motorola Polybend Technology</li><li>• Full features, similar to diesel</li><li>• Motorola 68336 micro @ 20 MHz</li><li>• Room for growth and improvements</li><li>• Knock detection and control</li></ul>	<ul style="list-style-type: none"><li>• 64K (bytes) Flash</li><li>• 3K RAM (total)</li><li>• 512 EEPROM</li><li>• Limited range Oxygen sensor</li><li>• 2 box system for engine &amp; speed control</li><li>• J1708/1587 datalinks</li><li>• Fiberglass PWB , obsolete technology</li><li>• Limited features</li><li>• Motorola 68HC11 micro @ 16 MHz</li><li>• Capability and throughput at limits</li><li>• No knock detection capability</li></ul>

The control system design including new sensors and actuators was completed. The field test engines were equipped with the full functioning system components. Delays in the humidity sensor development resulted in it being excluded from the final production release of the system. Development of the humidity sensor and control logic is continuing under a different project. When the humidity sensor and control logic development are completed, the implementation on the C8.3G Plus engine will be done through the regular current product change process.

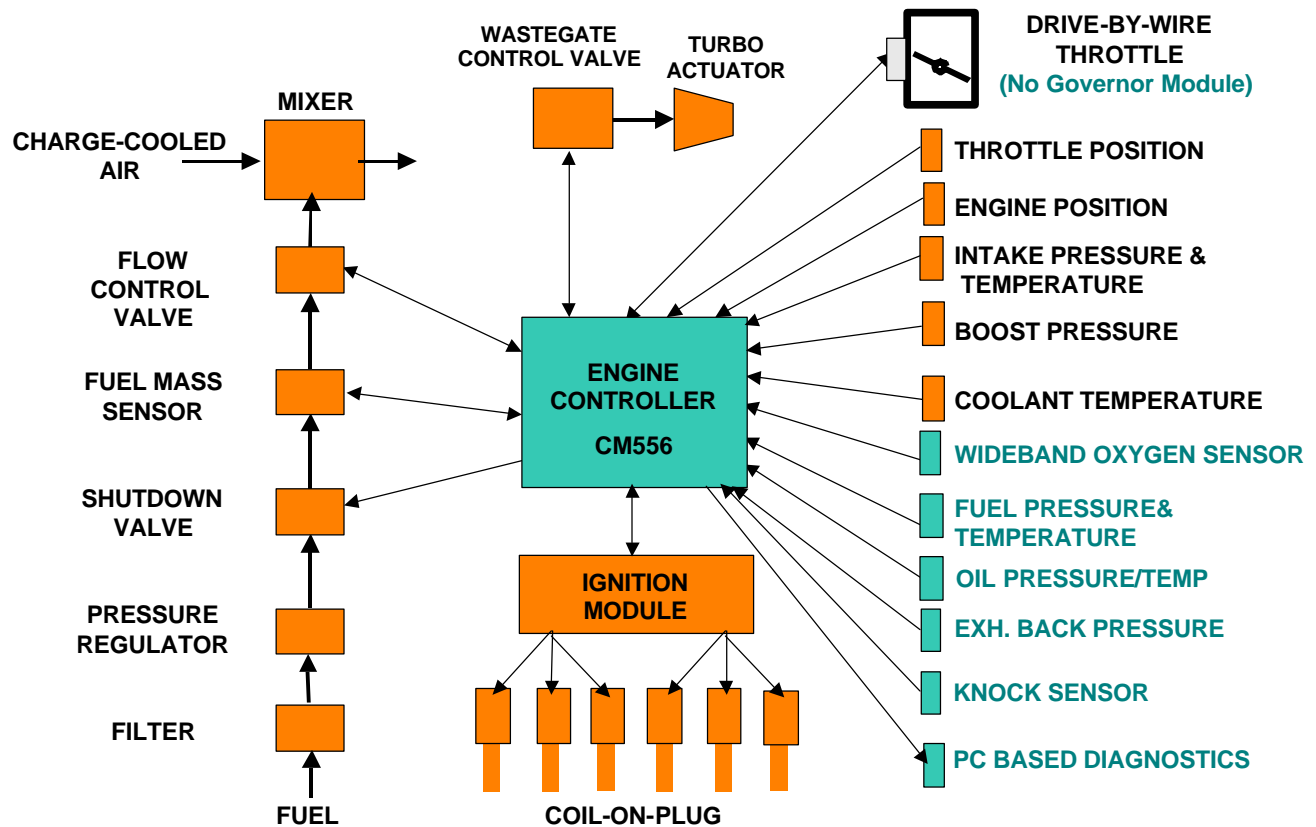
Validation testing of the ECM was completed prior to field test launch in the second half of 1999. All ECM hardware issues that were discovered in the design validation phase were corrected in the final hardware version. The final ECM design was extensively tested as part of validation testing for production.

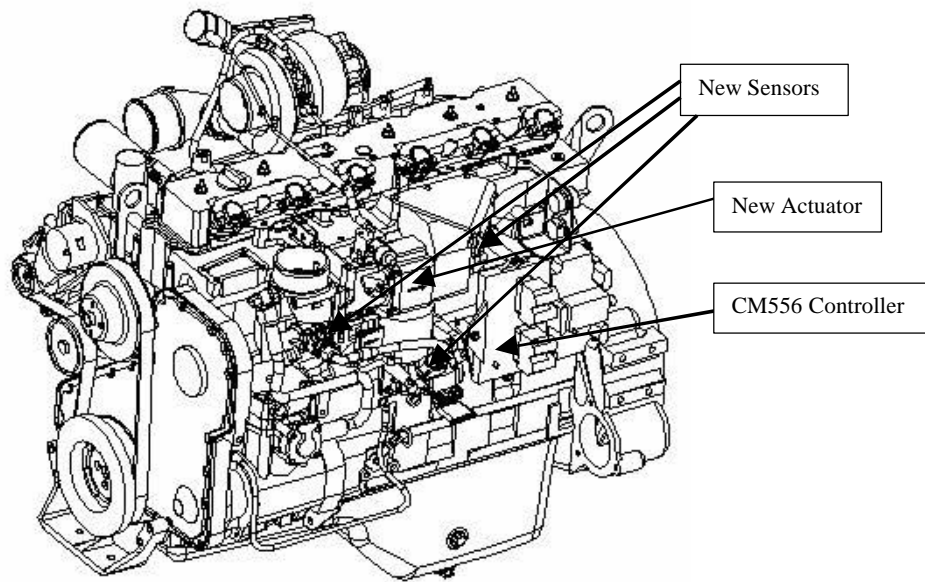
The control system facilitates the following features that highlights the robustness of the system design to the vehicle application needs:

- Robust Oxygen sensor
- Engine back pressure compensation

- Fuel supply pressure is measured
- Cooling fan drive available
- Knock sensing and control
- Intake Manifold Temperature (IMT) monitor and protection
- Supply voltage is measured
- Adaptive learn
- Engine mounted speed governor
- J1939 Datalink
- Diesel-like wiring
- Diesel-like features

## C8.3G Plus Control





## 1.2

Several revisions of the calibration validation work were performed to correct issues uncovered during the development and field test phases as well as to improve the overall system robustness.

field tests. Following final verification in the field and emission certification, the production software and calibrations were released to the producing plant for implementation.

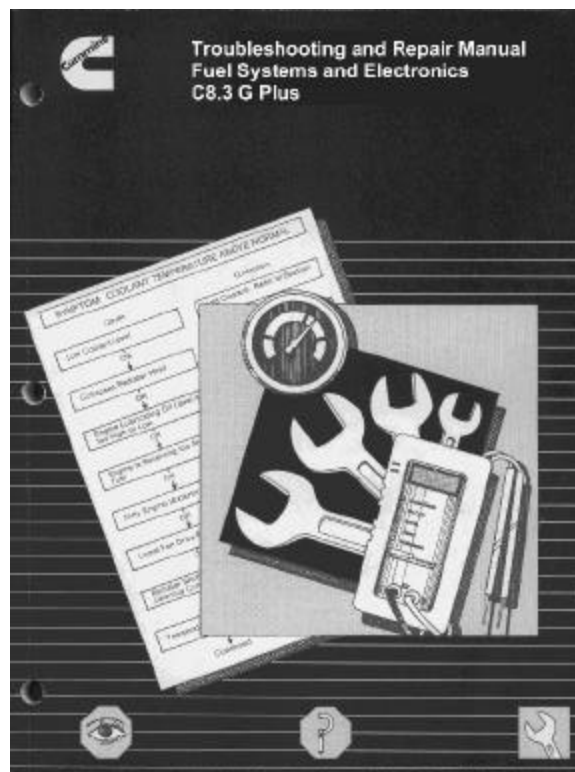
Revision #1 of the control software detected a few diagnostic false positives during the initial tests on field-test vehicles. Some of the faults were corrected by calibration adjustments, but there were

software. Verification testing was completed for all the final software diagnostic features and implemented in the production software.

production. The tool allows communication with the engine controller (CM556) for fault code evaluation and data logging. It also contains the troubleshooting and diagnostic system for the

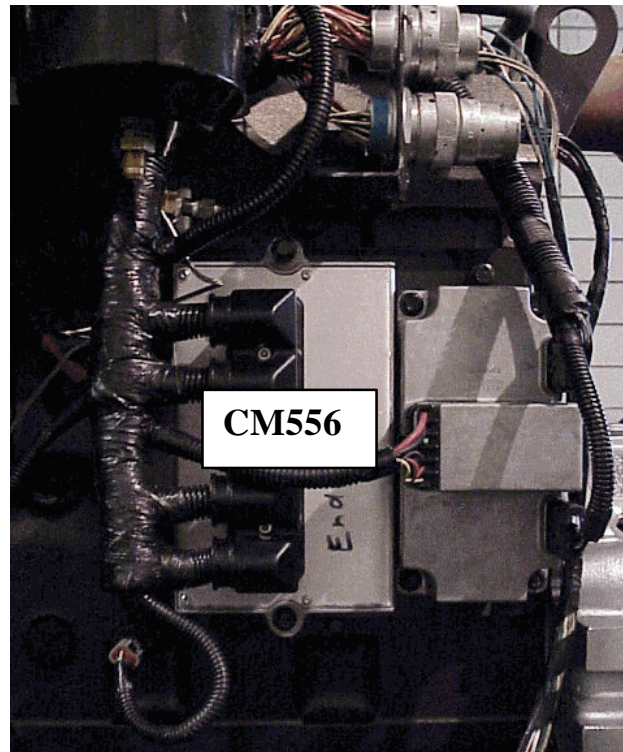


In addition, appropriate publications were developed and released to support the launch of the “Manual” that highlights the technique for troubleshooting an engine problem and the process of repairing field problems.



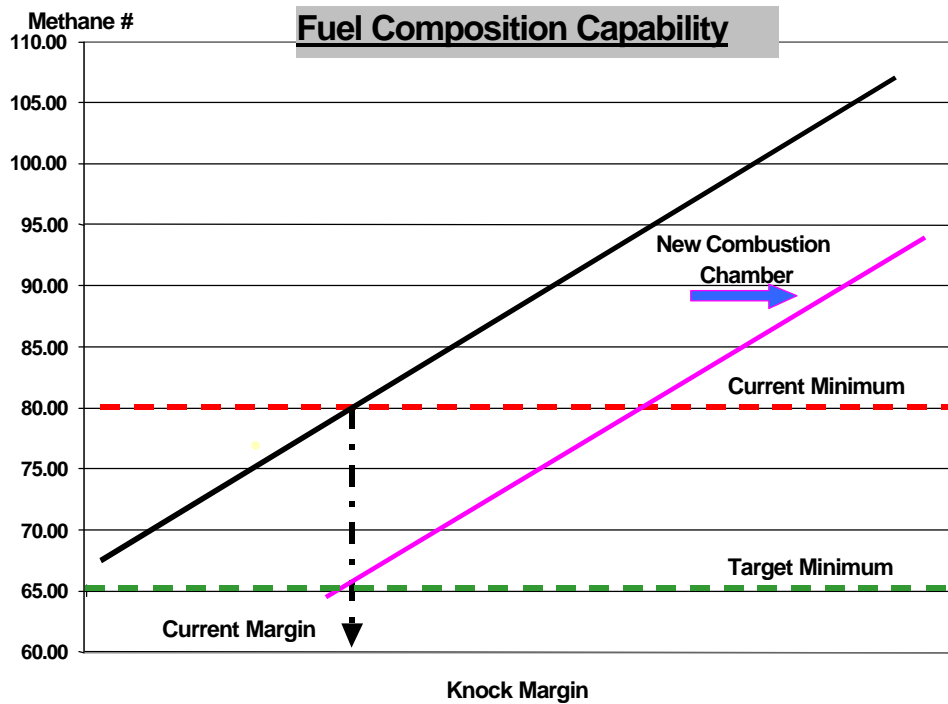
### 1.3 Harness design

To accommodate the new sensors and actuators employed in the new control system, a new engine harness was required. Thinner insulation wires were evaluated and selected to produce a manageable size harness. The harness design was finalized and released to production including the humidity sensor branch. Use of this branch, however, is pending sensor availability.



### 1.4 Fuel Specifications

Cycle simulation work was conducted to evaluate knock margin behavior for the available gas compositions. As shown in the graph below, the knock margin decreases linearly as the Methane number of the fuel decreases. The analysis was also used to predict knock margin trends with design changes in the combustion system. Shown in the graph is also the trend with a reduced compression ratio design (New Combustion Chamber) to achieve the desired knock margin with lower Methane number fuels.

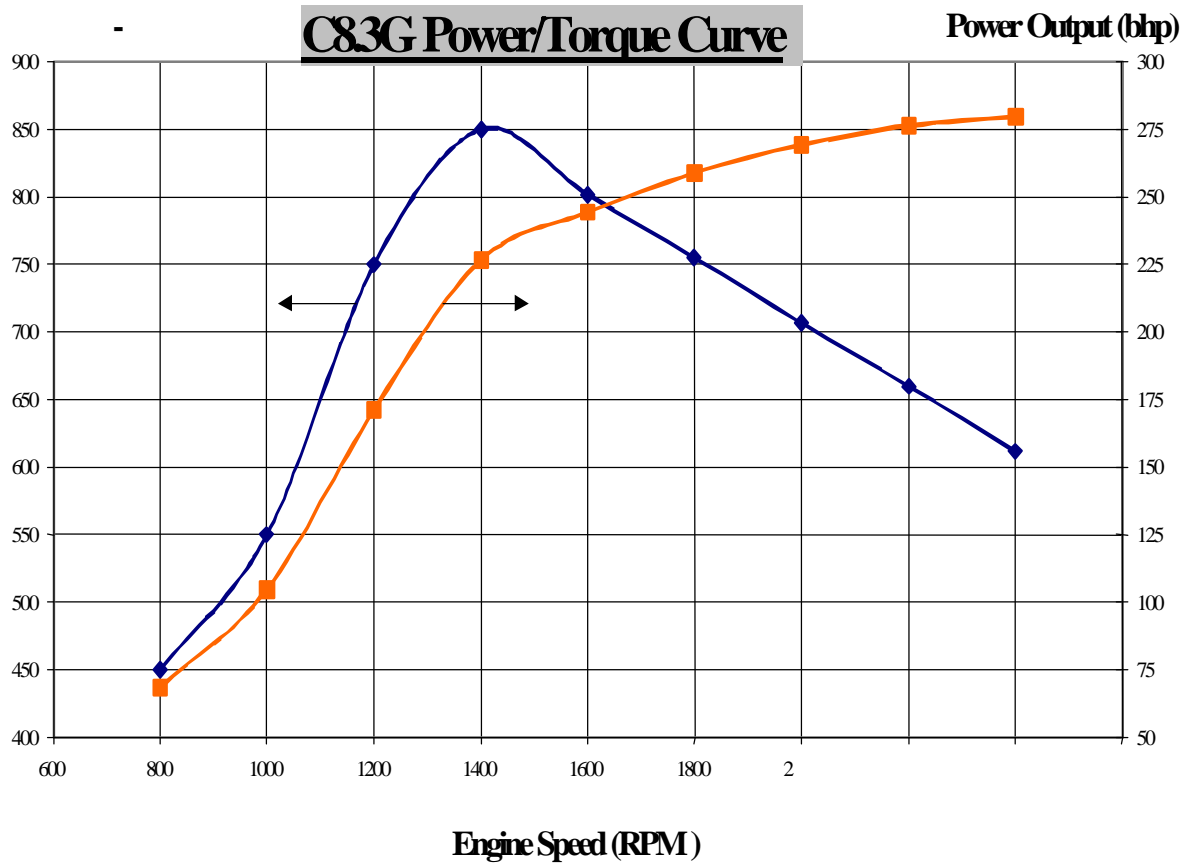


This data was used to select a minimum Methane number of 65 as the target of the widerange fuel capability for the project. The previous limit was 80 Methane number.

A specially formulated gas was procured to evaluate the predicted engine capability with low Methane number fuel. Test results confirmed the predicted capability of the design.

## 2. Performance Development

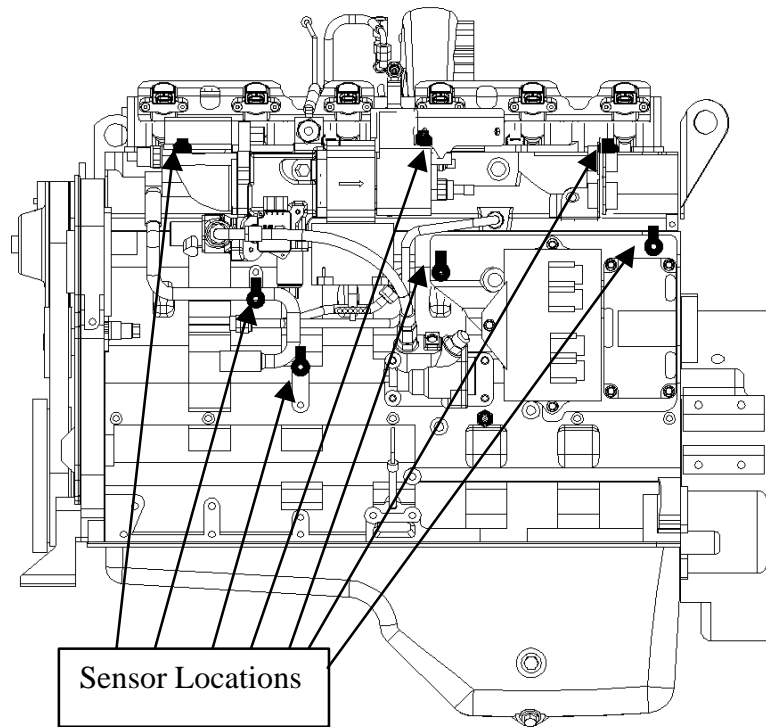
Combustion chamber design and performance parameter calibrations have been completed. The target performance goals for the engine including power and torque have been demonstrated with good compliance on all the engines built.



Part of the development plan was to release a humidity sensor into production as part of the engine management system. Available humidity sensor suppliers were contacted and parts were evaluated. However, issues were found with sensors meeting the design and operational requirements. These were not resolved in time for this project launch. This, however, did not affect meeting the development goals of the project.

Special hardware and software were developed to allow engine operation in knock mode of combustion in one cylinder at a time. Several locations were selected to locate the knock sensors. The capability of each sensor to detect the knock condition was evaluated with different knocking cylinders. Different knock intensities were also investigated. Two locations were finally selected that provided good coverage for all cylinders. These locations and the control logic were verified and developed by engine testing both in the lab and in the field.





### **3. Engine Builds**

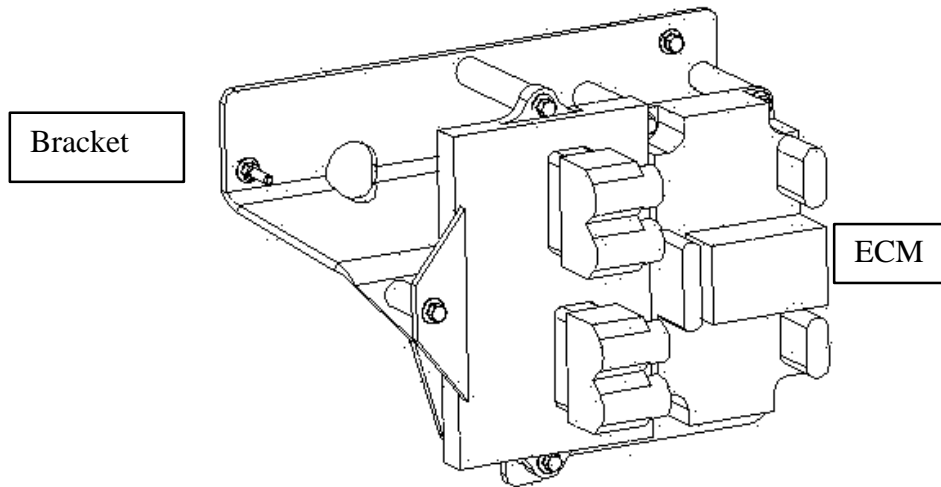
All planned field test engine builds and upgrade kit shipments have been completed. A total of 10 field test vehicles were tested as part of the verification program. These vehicles consisted of four complete field test engines and six hardware and software kits that were used to upgrade existing customer engines. In addition, six pre-production engines were built at the production facility. These included five customer engineering engines and one emission certification engine. The customer engines were funded by Marketing and were shipped to four bus OEMs and one international truck customer in Australia.

Build of production engine started in the plant in June 2001.

### **4. Mechanical Development**

A total of 4,500 hours of mechanical development tests were completed. This work was primarily focused on the power cylinder qualification tests for the new piston design and the new piston ring designs. The new rings were developed to improve the engine oil consumption and break-in performance. These tests were successful and included:

- Endurance tests at full load
- Cycle tests simulating light duty school bus duty cycle
- Thermal cycle test
- Overload test



Vibration profiles were obtained for the new critical components including the ECM mounting bracket, gas housing and sensor housing. These profiles were used to assess the durability of these parts. Bench qualification was completed for the ECM bracket (shown above) by conducting equivalent life tests on the bracket without failures.

## 5. Vehicle Demonstration

### 5.1. CTC Vehicle Tests

A transit bus vehicle located locally at the Cummins facility was upfitted with a prototype C8.3G Plus engine. The vehicle was used throughout the development program to develop and improve the control system. Good vehicle performance in the bus was achieved prior to release of the field test kits and engines. The vehicle was also later used as needed for further refinement of performance parameters and to verify new software and calibrations prior to field launch.



## 5.2 Field Test Engines

Four complete new engines were introduced for field evaluation. In addition, six additional upgrade kits were used to upgrade existing engines to the new engine configuration to expedite and increase the field test population. The table below outlines the field test units and locations. Also included below are pictures of some of these vehicles.

A total of 283,613 miles has been accumulated on the field test units through the end of May at which time tracking reporting process was stopped. The field test unit at London Transit has already been removed due to issues with the customer not providing the data required and refusing to make the necessary vehicle changes to optimize the power train. The two units at Viking trucking are still in operation.

Customer	Vehicle	Location	Engine/Kit
Sunline Transit	Bus	Thousand Palms	1
Waste Management	Truck	Palm Springs	2
Viking	Truck	Los Angeles	3
Viking	Truck	Los Angeles	4
Pierce Transit	Bus	Seattle/Tacoma	Kit 1 & 2
London Transit	Bus	London, Ontario	Kit 3
Phoenix Transit	Bus	Phoenix	Kit 4 & 5
Hamilton	Bus	Hamilton, Ontario	Kit 6

The table below shows the details of mileage accumulation in each of the field test fleet on a monthly basis. Also included in the table are the mile accumulations in time.

Customer	OEM	April Miles	May Miles	Jun Miles	Jul Miles	Aug Miles	Sep Miles	Oct Miles	Nov Miles	Dec Miles	Jan Miles	Feb Miles	Mar Miles	Apr Miles	May Miles	Total Miles
Phoenix 1	NABI		2809	2707	3405	3052	3050	169	2745	1653	876	1572	1680	3297	3976	30,991
Phoenix 2	NABI	1733	2332	2756	2917	3165	2985	2182	1738	1636	3122	1203	2441	3019	2911	34,140
Pierce 1	Newflyer	1640	4044	4466	4876	4857	5221	3958	4436	2464	1670	1678	351	4660	12591	56,912
Pierce 2	Newflyer	1629	5305	4713	3399	4869	4259	5569	4876	5044	4746	1944	3335	5969	3089	58,746
Hamilton St.	Orion		1665	1414	658	2429	2299	4423	1589	1229	3908	616	2606	2423	2323	27,582
London Transit	MCI			537	1134	2100	729	2093	3878	2591	2824	1447	2884	Removed	Removed	20,217
Sunline	Orion				770	3942	4841	4675	4315	3475	3975	2798	4547	3476	3601	40,415
Viking 1	Ford							379	619	735	556	475	579	739		4,082
Viking 2	Ford									0	0	327	1118	1034		2,479
Waste Man.	Mack										1975	3025	881	779	1389	8,049
TOTAL Fleet		5002	16155	16593	17159	24414	23384	23448	24196	18827	23652	15085	20422	25396	29880	283,613
Accumulated Fleet Total		5002	21157	37750	54909	79323	102707	126155	150351	169178	192830	207915	228337	253733	283613	283613



## **6. CARB / EPA Certification**

Transient cycle emission tests were conducted with the field test hardware, software and calibrations. Results indicated good compliance to the target levels of ULEV (2.5 g/bhp-hr NO<sub>x</sub>+NMHC). Further development was conducted to fully utilize the capabilities of the control system and as a result lower emissions were achieved.

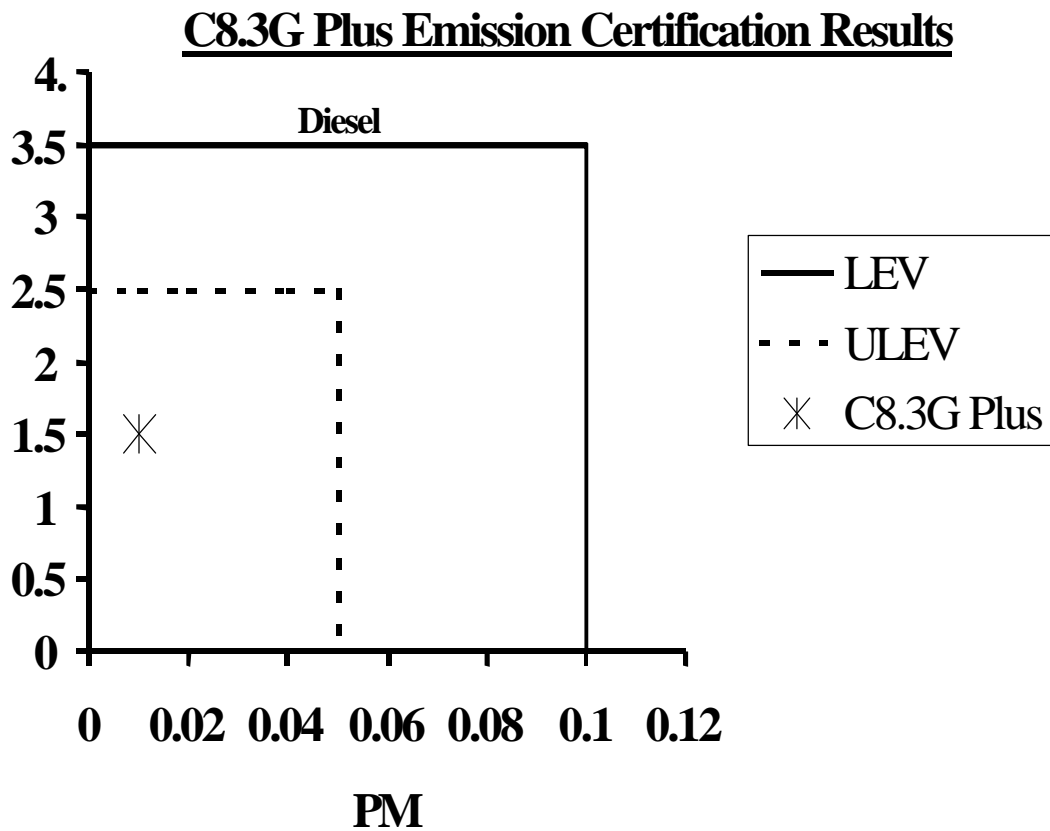
With an exhaust oxidation catalyst, the engine was certified to ULEV emission levels with the EPA and to a 2.0 (g/bhp-hr) optional low NO<sub>x</sub> level with CARB. The certification test results are listed below and show excellent compliance to the standard. Certification for LEV configuration has not been sought at this time.

The Supplemental Emission Test (SET) required for post October 2002 certification was also conducted and show good compliance to this upcoming standard. This data will be used to certify the engine to that standard at a later date.

### **C8.3G Plus Certification Test Results**

<b>Engine</b>	<b>NOx</b>	<b>NMHC</b>	<b>CO</b>	<b>Part</b>	<b>HCHO</b>	<b>THC</b>	<b>NOx+NMHC</b>
	<b>g/bhp-hr</b>	<b>g/bhp-hr</b>	<b>g/bhp-hr</b>	<b>g/bhp-hr</b>	<b>g/bhp-hr</b>	<b>g/bhp-hr</b>	<b>g/bhp-hr</b>
<b>C8.3G Plus (280/850) W/CAT (Transient Test Results)</b>	1.52	0.21	0.09	0.008	0.019	4.89	N/A
Deterioration Factor (Medium Duty/Automotive)	1.007	1.000	13.935	1.000	1.000	1.000	N/A
Deterioration Factor (Heavy Duty/Urban Bus)	1.011	1.000	21.671	1.000	1.000	1.000	N/A
<b>Certification Results (Medium Duty/Automotive)</b>	<b>1.5</b>	<b>0.2</b>	<b>1.3</b>	<b>0.01</b>	<b>0.01</b>	<b>4.9</b>	<b>1.7</b>
<b>Certification Results (Heavy Duty/Urban Bus)</b>	<b>1.5</b>	<b>0.2</b>	<b>2.0</b>	<b>0.01</b>	<b>0.01</b>	<b>4.9</b>	<b>1.7</b>
<b>C8.3G Plus (280/850) W/CAT (SET Test Results)</b>	1.35	0.01	0.06	0.005	N/A	2.72	N/A
Deterioration Factor (Medium Duty/Automotive)	1.007	1.000	13.935	1.000	1.000	1.000	N/A
Deterioration Factor (Heavy Duty/Urban Bus)	1.011	1.000	21.671	1.000	1.000	1.000	N/A
<b>Certification Results (Medium Duty/Automotive)</b>	<b>1.4</b>	<b>0.0</b>	<b>0.8</b>	<b>0.01</b>	<b>N/A</b>	<b>2.7</b>	<b>1.4</b>
<b>Certification Results (Heavy Duty/Urban Bus)</b>	<b>1.4</b>	<b>0.0</b>	<b>1.3</b>	<b>0.01</b>	<b>N/A</b>	<b>2.7</b>	<b>1.4</b>

These results are depicted in the graph below, which shows the significance of these emission levels compared to the standards. The “Plus” technology developed in this program has been proven to provide a significant improvement in the emission capability of lean burn natural gas engines.





## 7. Conclusions and Recommendations:

The key objective of this program was to develop and implement a modern electronic engine management system on a commercial natural gas engine. The following conclusions are drawn:

- Control technologies for commercial automotive natural gas engines have evolved from mechanical subsystems (e.g., air/fuel ratio controls) to electronic engine management systems. Electronic controls for natural gas engines have not kept pace with the rapid development of electronic controls for heavy-duty diesel engines in the 1990s.
- The design of the core-based electronic control hardware has been accomplished and verified for performance. The CM556 provides a significant advantage over the existing CM420 with respect to increased memory, speed, control inputs, control outputs, and application-specific features. Software for the CM556 controller has also been developed and tested.
- Extensive recalibration, taking advantage of the new control system hardware and software, has significantly reduced emissions and fuel consumption.
- The implementation of the CM556 has facilitated full control of air/fuel handling, drive-by-wire function, and eliminated a separate governor control module used with the previous natural gas engine platform.
- A set of new and improved sensors have been included in the C8.3G plus design. These contribute to a robust engine with greatly improved performance, emission, and diagnostic capabilities.
- Design changes have been implemented to enhance the robustness of engine performance and durability. The engine design, performance, and reliability with the CM556 control system have been validated through extensive bench, engine dynamometer, and field tests.
- The engine and controller design was evaluated and demonstrated in ten vehicle field tests in bus and truck applications.
- The C8.3G Plus engine has been emission certified including Supplemental Emission Tests (SET). The emission certification results at 1.53 g/bhp-hr NO<sub>x</sub> and 0.008 g/bhp-hr PM, with an oxidation catalyst, are the best in this class of natural gas engines. This NO<sub>x</sub> emission level is less than half of a similar diesel engine.
- CARB has certified the engine to the optional low NO<sub>x</sub> standard of 2.0 g/bhp-hr. The US EPA certification meets ULEV emission requirements. A family emission level for NO<sub>x</sub> was established at 1.8 g/bhp-hr. The Supplemental Emission Test (SET) required for post October 2002 certification test results shows good compliance.
- Natural gas fuel providers in the State of California and elsewhere are challenged to meet CARB fuel specifications for natural gas vehicle fuel. The octane rating and higher heating value of such fuels can result in performance issues, reliability concerns, and potentially progressive engine damage for engines without this new capability. The new capability to use a

wide range of fuel compositions as low as 65 Methane number has been validated in the laboratory.

- A parallel program delivered the electronic Service Tools and publications, complimenting the product launch for the field support and service organization. The Insite service tool and relevant maintenance publications have been released.
- The C8.3G Plus engine was launched into production in July 2001. All of the project deliverables have been met and some exceeded. Approximately 500 C8.3G Plus engines have been shipped in 2002. The customer response has been very positive. The current order board for this product is approximately 650 units.
- Senate Bill 199 (SB 199) Costs and Benefits. The project was performed within the costs proposed to the Energy Commission and the benefits achieved meet or exceed the expected benefits, from the development program.
- It is recommended that the same or similar controls be implemented with other natural gas products.